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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ON THERMAL EFFECTS IN RESONANCE TUBES

By Herbert Sprenger

Translation

"Über thermische Effekte in Resonanzrohren." Mitteilungen aus dem Inst. f. Aerod., No. 21, 1954, pp. 18-35 (see ref. 1).

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ABSTRACT

Thermal, acoustical, and pressure effects were observed in cylindrical tubes excited to resonance by a coaxial impinging gas jet. Temperatures up to 438° C were measured on the resonating tube walls, and temperatures above 1000° C were produced when suspended dust particles were present in the oscillating gas column. Maximum resonance occurred when resonating tube and gas jet nozzle diameters were approximately equal. Optimum resonating tube length-to-diameter ratio was found to be 34. The intensity of resonance produced by a subcritical gas jet nozzle pressure ratio was increased by the addition of turbulence-inducing threads in the nozzle exit. Resonating flow was simulated with a two-dimensional free-surface water-analogy model.

INDEX HEADINGS

Heat Transfer, Aerodynamic	1.1.4.2
Flow, Time-Dependent	1.1.6
Pipes	1.4.2.3
Research Technique, Aerodynamics	9.2.2

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SUMMARY

By periodic compression and expansion of a gas in a relatively rigid cavity, irreversible effects can create a temperature increase that may be a multiple of the adiabatic temperature head. This phenomenon is particularly pronounced if the gas volume oscillates with high-amplitude resonance oscillations. The experiments have been carried out with tube resonators that are easily excited by means of gas jets. It was found that, even with gas jets of subcritical pressure ratio (i.e., subsonic gas jets), intense oscillations could be obtained in the presence of slight instationary disturbances in the jet, such as are created by a fine wire extending across the jet nozzle (turbulence-creating wire). By this means, even the effect of hypercritical gas jets (i.e., supersonic gas jets) may be increased - an improvement that may perhaps also be useful with the ultrasonic generators of J. Hartmann. Measurements of pressures, temperatures, and sound intensities have been carried out with a large number of resonating tubes for frequencies of 50 to 3000 cps in air and excited by compressed air, using convergent nozzles with pressure ratios of up to 7 to 1, and also using a Laval nozzle for a Mach number of 1.7. Qualitative tests have shown that superheating may also occur with ultrasonic frequencies, although of lesser intensity. A maximum temperature rise of 450° C was obtained at the closed end of a thin-walled metal tube with an inner diameter of 0.3 centimeter and a length of 10 centimeters (at 900-cps sound frequency), excited by a coaxial air jet from a nozzle of 0.3-centimeter diameter at a distance of 1.2 centimeters. The air jet came from compressed air of room temperature at 4 bars pressure. By insulating the resonator and preheating the compressed air, the temperature rise can be further increased. With the thermal effects obtained in resonating tubes, exothermal processes can be initiated. To demonstrate this, a piece of wood with a hole drilled into one of its faces is sufficient. When an air jet from 3 to 4 atmospheres is directed against this hole from such a distance that intense resonance tones are audible, the wood starts to burn from within, giving off an intense smoke and bright sparks.

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If near the closed end of a resonator tube a small opening is made, such that part of the hot air which collects in the cavity can escape, the air coming out from the tube becomes cooler, having a temperature below the throttling temperature, corresponding to the heat of compression given off by the gas. Thus, resonator tubes can be used in the same way as Ranque's vortex tubes to separate expanding gases into heated and cooled partial jets. The characteristics of a "vortex tube without diaphragm" and of a resonator tube of the simplest design have been measured. The similarity of the curves obtained indicates a physical relation between the two separation processes.

INTRODUCTION

With the so-called "vortex tube" of Ranque (refs. 2 and 3), an expanding gas can be divided into separate hot and cold jets. In spite of numerous efforts (ref. 4), it has not been possible so far to explain the mechanism of this extraordinary temperature separation in an entirely satisfactory manner. It has been found that similar effects may also be obtained with other apparatus (refs. 5 and 6). In the present study an additional method for achieving this separation, the "resonance tube," is presented and considered in some detail.

The resonance tube is a cylindrical resonator, open at one end, which is excited to vibration by an impinging gas jet in the manner of the Hartmann ultrasonic generator (refs. 7 to 10). Tests were also conducted with a small opening at the otherwise closed end of the resonator tube through which part of the air escaped. The thermal efficiency of the apparatus is, for the time being, of little interest. The phenomena should be of practical significance for special problems and also for explaining and avoiding certain accidents in the field of high-pressure gas technology.

DESCRIPTION OF RESONANCE TUBE AND THE TEST SETUPS

Most of the investigations were carried out with axially symmetric setups according to the scheme of figure 1(c). The upper picture in figure 2 shows a typical test setup, and figure 3 presents several test results obtained with it. A gas jet coaxial with the opening of a tube resonator issues from a nozzle. The gas volume enclosed in the resonator (zone I in fig. 1) is compressed by the "gas piston" (zone II). The rising back pressure in the resonance cavity produces a side deflection of the nozzle jet (zone III). This, however, causes a pressure drop in the resonator, and its content in flowing back can again expand. The gas of zone II meanwhile escapes into the outer space, while the gas of zone I remains in the resonator. The processes can be repeated in periodic sequence if the effective pressures and the geometric dimensions assume certain values. In the case of resonance, the gas content (zone I) is excited to longitudinal oscillations with large amplitude. The intensity of the oscillation depends on the nozzle pressure ratio p_0/p_k, the ratio of the nozzle exit and resonator inlet areas d/D, the ratio of the distances between nozzle and tube l/d, and on the dimensions of the tube L/D as well as on damping effects. The damping is exerted by the wall friction, the elasticity and porosity of the resonator material, and the inertia forces of the suspended particles. The fundamental frequency f of a resonator oscillation can be estimated from the length L of the tube: $f = a/\lambda \approx a/4L$, where a denotes the sonic velocity of the gas and λ the wave length. (The muzzle correction, the mixing and diffusion processes between the zones, and other secondary effects are not taken into account in this estimate.)

For the study of the mechanisms that support and control the oscillation, tests were carried out with water as flow medium in a plane model of a resonance tube according to figure 1(b). In accordance with a suggestion of Professor J. Ackeret, we employed the analogy between gas-dynamic processes and "water currents with free surfaces" (see E. Preiswerk, ref. 11) for investigating this nonstationary problem. A model was constructed out of a sheet-metal strip 4 centimeters wide, in which the nozzle opening and the distance between nozzle and channel inlet l could be varied. Good oscillation conditions are established, for example, for the following dimensions: channel length L, 20 centimeters; channel width, 4 centimeters; nozzle opening, 3 centimeters; distance l, 6.5 centimeters; mean depth of water, 3 centimeters. Under "flowing" (Mach number $M < 1$) and "shooting" ($M > 1$) conditions of the arriving stream, intense resonance oscillations could be demonstrated with this apparatus. The frequency of the fundamental oscillation is approximately $f = 1$ cps ($L = \lambda/4$). With patience it is also possible to set up the higher harmonics ($\lambda = 3\lambda/4$ and $5\lambda/4$). The level fluctuations (amplitude, approx. ± 1 cm) are a measure of the pressure variations. Particles floating, or rather suspended, in the water show the self-excited flotation motion (displacements up to $L/2 = 10$ cm), as well as the occurrence and paths of the vortices, the position of the stagnation point, and the characteristic differences of the processes in the zones I, II, and III. With the model test it is further possible to show that the oscillation state remains the same within wide limits if, during the operation, water is removed from or added to zone I.

In the pipes of figure 1(a), such as those used in organs, no heating could so far be established. In numerous sound generators constructed according to figures 1(b) and (c), however, thermal effects could be demonstrated. Pipes of this construction normally oscillate only at above-critical (supersonic) pressure ratios. With the aid of turbulence-producing means in the free jet, it was possible to operate the resonance tubes (hence also the Hartmann "air-jet generators") with gas jets at subsonic velocities and to obtain increases in temperature. Threads stretched across the nozzle outlets are particularly helpful. Nylon threads of 0.001-centimeter diameter were glued to the rims of the nozzle.

The literature on ultrasonic pipes (refs. 7 to 10) contains no reference to the temperature phenomenon considered herein. The phenomenon was probably unobserved only because the sound generators excited with gas jets, such as are constructed for numerous physical and technical purposes, possess massive metal resonators in which temperature differences are rapidly canceled out.

For the investigation of thermal effects, resonators constructed of poor heat-conducting materials were used; while, for the temperature measurements, cylindrical, very thin-walled tubes of nickel silver were used. In the case of all the results reported herein, small tubes of 0.3-centimeter internal diameter and 0.01-centimeter wall thickness were employed. Iron-constantan thermocouples 0.01-centimeter thick, soldered to the surfaces or exposed to the gas, served to determine the mean-temperature values of the tube walls and the various gas jets.

The temperatures, t° C, and the pressures p are further specified by the following subscripts: w, values determined on the warm side; k, values determined on the cold side; F, surface near the resonator end; 0, stagnation condition of the gas under pressure.

In the case of gas jets it is customary to give all the measured and computed temperatures as absolute temperatures, T° K, and as a difference with respect to the stream temperature T_{∞}. The stream temperature is the adiabatically computed temperature in the expansion of a gas from the rest pressure p_0 and rest temperature T_0 to the final pressure p_k. In the entropy diagram shown in the lower right-hand corner of figure 3, the thermodynamic definitions are indicated.

$$T_{\infty} = T_0 - \Delta T_{ad},\ \Delta T_{ad} = T_0\left[1 - \left(\frac{p_k}{p_0}\right)^{\frac{\gamma-1}{\gamma}}\right] \qquad (1)$$

where $\gamma = c_p/c_v$ = ratio of specific heats of the gas. The characteristic temperature ratio (ref. 5) is defined as:

$$\beta = \frac{T - T_{\infty}}{T_0 - T_{\infty}} = \frac{T - T_{\infty}}{\Delta T_{ad}} \qquad (2)$$

The temperature difference, $T - T_{\infty}$, is not directly measurable; only the difference above the rest temperature T_0 of the compressed gas, $T - T_0$, is measurable.

Since $T - T_{\infty} = T - T_0 + \Delta T_{ad}$,

$$\beta = 1 + \frac{T - T_0}{\Delta T_{ad}} \qquad (3)$$

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The following conditions are of special significance:

$\beta = 1$ static temperature of the compressed gas before the expansion or stagnation temperature after adiabatic recompression from T_∞

$\beta = 0$ stream temperature after adiabatic expansion, or the temperature readings of a thermometer moving with the stream

The temperature changes due to the Joule-Thompson throttle effect, ΔT_{JT}, constitute only a very small percent for the processes considered herein; where necessary, they can be taken into account as additive corrections. If, for example, air ($\gamma = 1.4$) is expanded from $T_0 = 293^\circ$ K ($t_0 = 20^\circ$ C) by throttling from $p_0 = 5$ bars[1] to $p_k = 1$ bar, then $\beta_{JT} = 0.998$ and $\Delta T_{ad} = 108^\circ$ C so that $\Delta T_{JT} = T_0 - T_0' = 0.208^\circ$ C; that is, $T_0' \cong T_0$.

If gas is expanded by throttling from the state p_0, T_0 to p_k, T_0 and then is again compressed to the pressure p_0, the adiabatically computed final temperature is

$$T_1 = T_0\left(\frac{p_0}{p_k}\right)^{\frac{\gamma-1}{\gamma}} \tag{4}$$

and the corresponding characteristic temperature ratio is

$$\beta_1 = \frac{T_1 - T_\infty}{T_0 - T_\infty} = 1 + \frac{T_1 - T_0}{\Delta T_{ad}} = 1 + \left(\frac{p_0}{p_k}\right)^{\frac{\gamma-1}{\gamma}} \tag{5}$$

In the case of the numerical example just given, there is obtained: $\beta_1 = 2.58$, $T_\infty = 185^\circ$ K so that $T_1 = (\beta_1 \cdot \Delta T_{ad}) + T_\infty = 464^\circ$ K ($t_1 = 191^\circ$ C) and $T_1 - T_0 = 171^\circ$ C. This optimum increase through recompression, β_1, lies far below the measured values. In the tests with oscillating gas columns, tube wall temperatures $t_F = 438^\circ$ C (above 1000° C) were measured under these operating conditions after a short time. The corresponding characteristic temperature values are $\beta_F = 4.87$ (about 10). In order to attain these temperatures through adiabatic recompression, compression ratios of 22.5:1 (240:1) were required (the values in parentheses correspond to a measurement with suspended dust particles in the resonance cavity of zone I).

Resonance tubes as shown in figure 1(c) are particularly well suited for investigations since, with this two-part arrangement, the nozzles and resonators can easily be interchanged and the distance l can be changed during the operation. Picture (a) in figure 2 shows the

[1]One bar is equivalent to 1019.7 grams force/per square centimeter.

micrometer spindle for displacing the nozzle in the axial direction and the tube support in the shape of a disk. The disk protects the tube end on the warm side from cooling by the outflowing air jet, deflecting the flow radially. Further measures for decreasing the loss of heat were not taken for the measurements reported herein. Of importance is accurate coaxial positioning between nozzle and tube; cross displacements and errors in angles reduced the thermal effects. (This sensitivity explains certain scatterings of the measured values and gives suggestions for reducing the heating phenomena in technical armatures and apparatus for compressed gases.) On the optical bench (fig. 2) are a measuring rod, two nozzles of different shape, and three diaphragms that can be mounted on the warm side. The figure 2(b) and (c) series of pictures are schlieren pictures with a spark source; see the description given with figure 2.

An interesting, although not clearly defined mean pressure value, $\overline{p}_W$, of the pulsating stream could be measured with the aid of a static connection near the resonator end. A steel capillary tube of 0.01-centimeter internal diameter and 40-centimeter length led to a Bourdon or mercury manometer.

A sound-intensity meter (General Radio, type 759-B), set up laterally at a distance of 100 centimeters from the nozzle opening, served to determine the radiated sound intensity in the audible frequency band between 20 cps and 15 kcps. The ultrasonic range was observed only optically. The strongest heating occurs coincident with the loudest noise; see figure 3, lower curve.

The electrical voltage fluctuations of a microphone exposed to the air noise show complicated oscillation patterns on the cathode-ray screen during operation of the resonance tube. The fundamental tone is not in the form of a sine wave. Moreover, it has superposed on it numerous higher frequencies and a strong noise level. The oscillation pictures vary because of changes in the air speed and the free jet length and can hardly be further identified for the optimal heatings, for which case a characteristic crackling noise can be heard. Better views of the nonstationary processes are obtained by mounting a vibration detector on the end of the resonance tube. The pictures are no longer obscured by the noise of the air jets; the curves are more reliable. The rise during the compression stroke is so steep that the occurrence of shock waves may be presumed. Frequently, after about a quarter-wave length, two smaller peaks may be made out.

RESULTS OF MEASUREMENTS

The following ranges of the magnitudes of influence were covered in the tests:

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(1) Expansion against the atmospheric pressure $p_k \approx 1$ bar from the static pressure $p_0 = 2.5$ to 7 bars or, with turbulence producing threads, $p_0 = 1.2$ to 2.5 bars

(2) Nozzles of different shape with the outlet diameter $d = 0.1$ to 1.2 centimeters

(3) Tube resonators of internal diameter $D = 0.08$ to 1.5 centimeters and lengths $L = 0.2$ to 600 centimeters of various materials

It is very probable that strong thermal effects arise also in resonance tubes of large dimensions, while for tubes of small dimensions ($D < 0.1$ cm) such effects are difficult to detect.

High temperatures arise if $d \approx D$. In the pressure-ratio range between 6:1 to 3:1, small changes of l/d and of p_0/p_k produce large fluctuations of the tube wall temperatures ($\beta_F = 1$ to 5). If $d < 0.9$ D, this sensitivity vanishes. In addition to the fundamental tone, overtones can also be heard; the maximum temperatures are lower, however ($\beta_F < 3.5$).

In figure 3 are plotted the results of a measurement for the above-critical pressure ratio $p_0/p_k = 5$ against the length ratio l/d. Two temperature scales are used; one divided into degrees Centigrade ($t_0 = 20^\circ$ C), the other indicating the characteristic temperature ratio β. On all three curves, resonance peaks are clearly evident. These peaks arise if the resonator opening is situated within the jet zones where a pressure rise occurs. In the zones with overexpansion, the resonance excitation vanishes. The excitation of oscillations with above-critical expansion of the gas jets has been very accurately investigated for the case of ultrasonic generators (refs. 8 to 10), so that it is not necessary to consider it here in more detail. In the first compression zone the excitation of oscillations is generally weak, while within the second compression zone the most intense tones and the maximum temperatures are almost always produced. From the sixth compression zone on, the relations change fundamentally because the standing wave structure of the jet is weakened. From $l/d = 12$ on, overtones can clearly be heard. For $l/d = 4$, $t_F = 440^\circ$ C, $\beta_F = 4.9$, $\bar{p}_w = 4.5$ bars, and the sound intensity is 115 decibels.

On all figures the nozzles (in true proportion) used in the measurements are always shown. The most favorable nozzle had, following the contraction, a two-diameter (2d)-long parallel section for the gas jet. In the comparison measurements (figs. 6 to 11) the ordinate scale for β_F was kept constant, while the abscissa scale for l/d was adjusted to produce the desired effect. It was possible to dispense with mean-value determinations of the sound intensity and pressure after their variations with temperature were clarified in the manner shown in figure 3.

Figure 4 shows measurements similar to those of figure 3 but carried out with a subcritical nozzle pressure ratio. At $p_0/p_k = 1.45$, the air leaves the nozzle with a velocity corresponding to the Mach number $M = 0.75$. The pressure ratio, instead of the Mach number, is given as a parameter because the baffle effect of the resonator influences the exit velocity. In this example the optimum of the wall temperature ($\beta_F = 3.6$) lies at $l/d = 1$. The mean pressure at the end of the tube p_W nearly attains the static pressure p_0 at this operating point.

Figure 5 gives the surface temperature distributions along the tube axis for the adjustments with optimum heating according to figures 3 and 4. For larger pressure ratios, the rise is retarded and the curve is steeper. (The optimum β_F values lie somewhat higher than in figs. 3 and 4 because the thermocouple was attached with a heat-insulating asbestos thread.)

The effect of the length of the tube resonator on the heating was investigated, and the resulting measurements are shown in figure 6. In addition to the length ratio L/D, the frequency of the fundamental oscillation (f, cps) is also given. Optimum temperatures occur for tube lengths $L = 34D$. In shorter tubes the mixing of the gases of zones I and II probably has a weakening effect, whereas in the case of the longer tubes the cooling surfaces are larger. In addition, too strong a damping can also lead to a temperature drop. More accurate investigations must take into account not only the temperature but also the heat production.

Figure 7 shows the temperature at the end of the 900-cps resonator tube for excitation by above-critical expanding gas jets. At the pressure ratio 4:1 the resonance peaks are very narrow and sharply pronounced. For this pressure ratio, $\beta_{opt} = 4.6$, $\Delta T_{ad} = 96^\circ$ C, $T_F - T_0 = 3.6 \times 96 = 345^\circ$ C, $t_F = 365^\circ$ C; and, for the ratio 7:1, $\beta_{opt} = 4.45$, $\Delta T_{ad} = 125^\circ$ C, $T_F - T_0 = 3.45 \times 125 = 430^\circ$ C, $t_F = 450^\circ$ C. (Smaller β values can also, according to the definition, lead to higher temperatures.)

The results of four measurements at below-critical compression ratios and with oscillations excited by means of a 0.001-centimeter turbulence wire are given in figure 8. The exit velocities from the nozzle lie between the Mach numbers 0.5 and 0.95. Note in particular the insensitivity of the optimum position l/d with respect to changes in p_0/p_k. The resonator oscillates always with the fundamental frequency $f = 900$ cps and is independent of the pressure variation. (Galton's whistles and organ pipes change their frequency strongly with the expansion pressure ratio; for organ pipes $p_0/p_k < 1.05$; hence, $M < 0.25$).

After successful use of air jets with $M < 1$ to produce intense resonance oscillations, the nozzle with turbulence wire was also tested for above-critical pressure ratios. The tests lead to the interesting result that considerable increases in intensity can be attained up to the value $p_0/p_k = 4$. The effect is shown in figure 9 for the pressure ratio 3, the turbulence wire increasing the intensity for the 900-cps tube by the factor of 4.

To produce particularly intense ultrasonic oscillations in air with Hartmann generators, several authors (ref. 8) recommend sharp-edged diaphragms in place of nozzles. Figure 10 shows that for the pressure ratio 5:1 the nozzle with the parallel duct is still somewhat better with regard to the temperature rise.

In the application of propulsion jets that are produced in Laval nozzles, the thermal effects in resonance tubes arise in a somewhat different manner (see fig. 11). (The Laval nozzle was designed for the pressure ratio 5:1 ($M = 1.7$); diameter at the narrowest section, 0.24 cm.) The temperature rise of the tube wall starts at $l/d = 0.2$. The numerous small β peaks always appear when acoustically strong overtones can be perceived. In the case of the Laval nozzle the turbulence wire produces practically no temperature rise.

DEMONSTRATION EXPERIMENTS

The thermal effects in resonance tubes can readily be demonstrated. It is of advantage for this purpose to employ resonators of combustible materials, for example, a block of wood with a hole bored in it. If a compressed air jet is directed against the hole in such a manner that strong resonance oscillations arise, the temperature of the gas in the cavity can rise far above the ignition temperature. In operating with compressed air, cavities can be burned out in this manner. If pure oxygen is used for the experiment, the process takes place with extreme intensity; in a few seconds deep craters are produced and the nozzle may be destroyed.

Figure 12 shows the result of an experiment with air ($p_0 = 3.5$ atm abs, $t_0 = 20^\circ$ C, $d = 1$ cm, and $l = 4$ cm). The bore in the hole was initially 6 centimeters deep ($L/D = 5$, $f = 1800$ cps). Since the length of the resonator also increases in the burning process, the frequency drops. In the hot zones wood tar is formed. The easily flowing tar is, over an extensive area of the hole, forced between the wood fibers up to the external surface by the action of the gas pressure. After 30 seconds the cavity shown is burned out. Of striking effect are the charcoal swellings formed transverse to the direction of oscillation, perhaps a consequence of secondary flows and standing waves.

By blowing air for a sufficiently long time, very large cavities can be produced. When the cavities have attained a certain size, it is possible that the longitudinal oscillations cease along with combustion.

(Still larger cavities can be burned out by further blowing in an obliquely tangential direction; the combustion then is supported by an intense cyclonic flow.) Practically all types of wood are suitable for the tests. If the wood is very permeable to gas, the ignition temperature is reached with difficulty, and long tubelike incendiary scars are formed. Impregnated heavy woods similarly do not burn well; pear-shaped cavities are formed. Optimal effects are produced by borings of the dimensions $L/D = 5$ to 20.

Further phenomena produced in wood by resonance oscillations are sketched in figures 13(a) and (b). The heavy dashed lines denote the original hole dimensions. The combustion process is indicated in three different stages. At (a), to the left, the wood wall burns through in the direction of the jet; simultaneously, the oscillation and the combustion processes vanish. Generally, in thick pieces of wood, for sufficiently long blowing under resonance conditions, secondary channels arise laterally near the original boring (see (b)). The standing oscillation of the gas column acts similarly in this side branch; wood tar first appears at those places of the surface at which the burning-through later occurs. The burning out of cavities can also be effected through conical and very short cylindrical holes. In short resonance cavities the temperature can be strongly reduced, for example, by the action of a roundhead nail, driven into the base of the hole (see fig. 13(a)). Burned out cavities can also be produced with the aid of a piece of pipe knocked into the wood.

By means of resonance oscillations it is also possible to produce melting processes. The "temperature transformation" depends on the static temperature T_0 and the pressure ratio p_0/p_k. (By heating the compressed gas before the expansion, very high gas temperatures probably can be produced with this process; it would be of interest to investigate the resonance tube process under extreme temperature and pressure conditions, with respect to its effect on the gas itself and on the material of the resonance cavity (in particular, for the application of CO_2, heavy inert gases, etc.).) Our "model tests" were carried out at $t_0 = 20^\circ$ C in materials with correspondingly lower melting points (paraffin, sealing wax, hard rubber). In figure 13(c) several cavities produced by melting in paraffin are sketched. The thermal effects again begin at the resonator end. The molten paraffin during the resonance process is transported out of the bore in very fine droplets during the expansion stroke. At the start of compression several of the paraffin particles are thrown against the frontal surface of the body; they collect as a bulged rim around the resonator opening. The melting process comes to an end when the cavities have grown to about three times the diameter of the bore. In very short holes ($L < 0.5$ D) no melting processes can be produced in paraffin; a temperature rise, however, still existed (indicated by a thermocouple). For the pressure ratio 1.6 it was still possible, in holes of length $L = 10$ D, to melt out caverns with the aid of the nozzle with turbulence wire.

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Figure 13(c), right, shows the case for which warm gas from zone I can escape into the surrounding atmosphere through a narrow bore. Its excess temperature ($t_W > t_0$) and the cooling of the back-flowing gas from zone II ($t_k < t_0$) can easily be demonstrated.

Figure 13(e) shows the deformation of a tube of a thermoplastic material whose gas content was brought into resonance oscillation. For comparison there is drawn above it the tube in its original state. Successful tests of this kind were also obtained with 400-centimeter-long tubes (f = 25 cps). Bent tubes show that the thermal effects are only insignificantly weakened through curvatures of the tube axis.

Figure 13(f) shows a nickel-silver tube on which temperatures of over 1000° C were measured. The end of the tube glows and melts down. The cause of the temperature rise from $\beta_F = 5$ to 10 was the tin used to solder the plug at the resonance end, which flowed into the interior of the tube. During the oscillation process the tin melts and is suspended in the air of zone I. A part also flows as a fine black dust through zone II to the outside. The temperature rise is very probably caused both by the action of the intensified damping, together with mechanical friction of the particles at the wall, and by oxidation. Also, traces of glass dust, talcum, and so forth brought into the resonators bring about a rise of temperature. For the purpose of avoiding this side effect in the measurements corresponding to figures 2 to 11, the tube plugs were not soldered in place but were pressed in.

COMPARISON OF RESONANCE TUBE WITH VORTEX TUBE

Figure 14 shows the interesting comparison of the separation characteristics of a vortex tube and a resonance tube. Both devices are constructed in the simplest manner and are operated under the same operating conditions ($p_0/p_k = 5$, $t_0 = 20°$ C) for equal contraction ratio in the nozzle (d = 0.3 cm). The mass of air flowing in per second (m_0) was the same for the vortex tube W as for the resonance tube R. During operation the temperatures t_w and t_k of the issuing air masses m_w and m_k were measured. After issuing from the throttle valve, the warm air flowed first through a cooler and then through a gasometer. The gas mass on the cold side $m_k = m_{II} + m_{III}$ is obtained as the difference $m_0 - m_w$. The absolute accuracy of the measurement is estimated to lie in the range ±5 percent. Since both devices were investigated with the same means, the characteristics for judging their similarity are sufficiently accurate.

The vortex tube of simplest construction possesses no diaphragm. A 60-centimeter-long tube of 1-centimeter diameter, at whose center the gas jet entered tangentially, was used. If the same air quantity issues on both sides, no temperature changes occur. Warm air flows forth always on the side of the tube that is more strongly throttled. The operating characteristic of such a tube is symmetrical, for which reason only half of it is represented in figure 14. From the measurements of Hilsch (ref. 3), it follows that, with the type of construction he used, the degrees of cooling decrease and degrees of heating increase as the diaphragm diameters are made larger. Optimum excess temperatures therefore occur for the vortex tube without diaphragm. Its characteristic is compared with that of the 900-cps resonance tube shown in figure 14, in which the temperatures t_k and t_w of the partial gas jets are also plotted against the distribution ratios m_k/m_0 and m_w/m_m (their sum is 1). In both devices the cooling effects are relatively weak. In the case of the vortex tube the optimum value lies at $\beta = 0.91$, whereas for the resonance tube the value 0.935 is reached. (With the best "Hilsch tubes" coolings up to $\beta_k = 0.4$ can be attained.) The great similarity of the two separation characteristics supports the idea of Professor J. Ackeret that the processes in the two devices are physically related. Actually, intense sound vibrations can also be observed in vortex tubes (see author's paper, ref. 4).

The thermal effects in resonance tubes were investigated at the Swiss Technical College at Zurich in the spring of 1952. All apparatus and installations were produced in the workshops of the Institute for Aerodynamics, for which the author desires to express his thanks to Messrs. E. Hurlimann, H. Isler, and A. Weiss. The author wishes to express his sincere thanks to his very honored chief, Dr. J. Ackeret, for the promoting and publication of this work.

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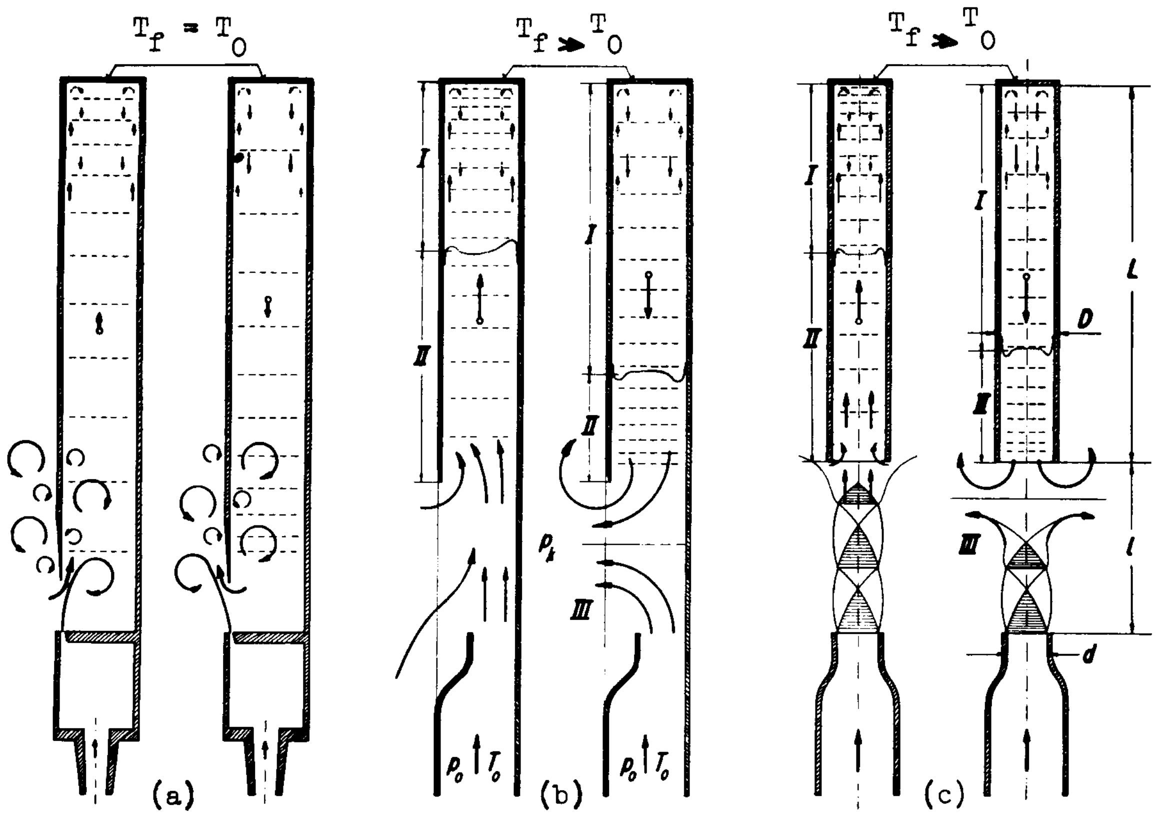
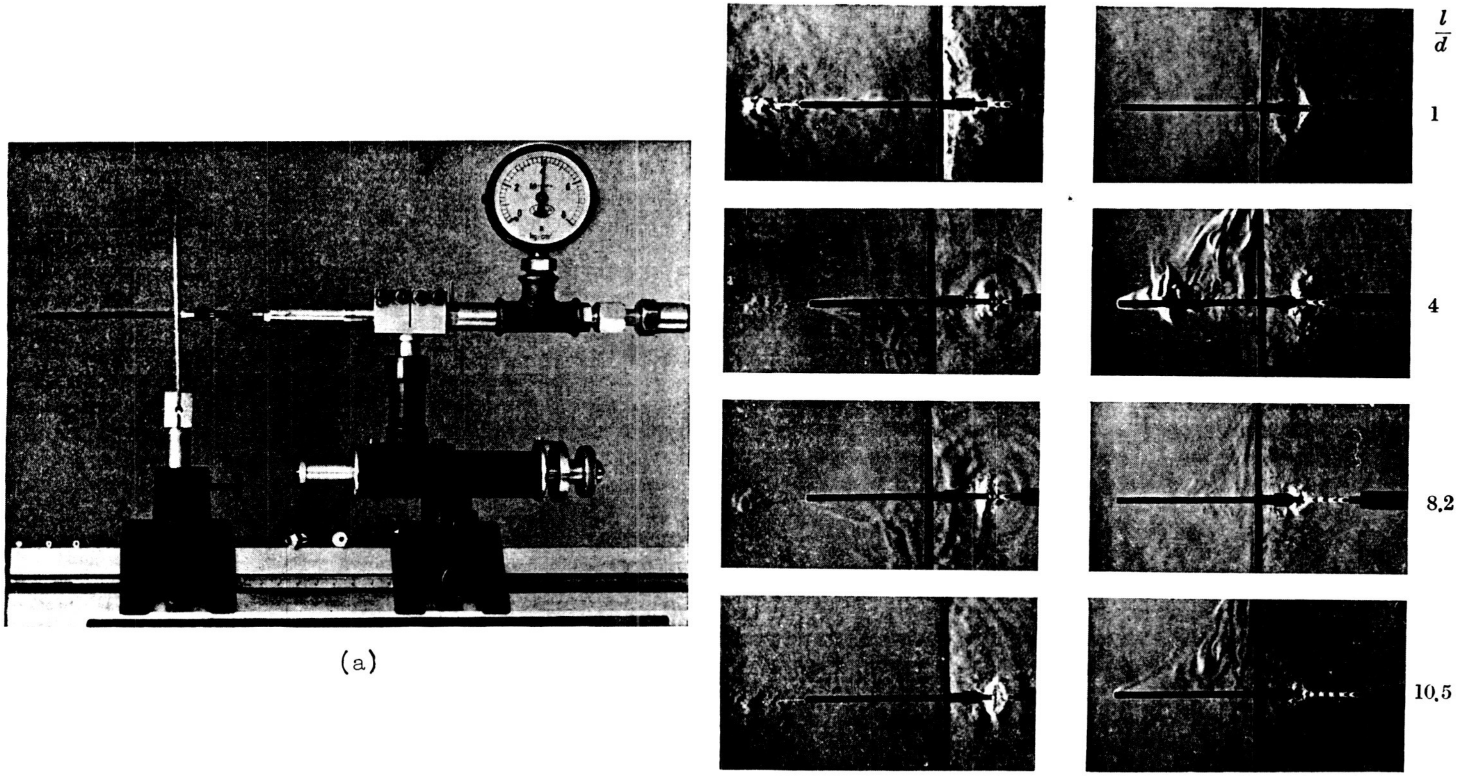


Figure 1. - Tube resonators closed at one end, excited to oscillation by gas jets. (a) Lip pipe for small pressure and motion amplitudes (organ pipe). (b) and (c) Lip pipes for large pressure and motion amplitudes. (c) Corresponds to rotation symmetry construction of (b); flow of gas jet for above-critical nozzle pressure ratio.
A compression and an expansion phase are represented. In operating with air at room temperature (20° C), gas volume of resonator (a) undergoes no temperature rise, whereas excess temperatures of 500° C and over, due to oscillation process, can be measured for pipes (b) and (c) in region of closed ends.



(a)

(b)

(c)

Figure 2. - 900-cps Resonance tube, measuring apparatus, and instantaneous schlieren pictures. Operation with air at pressure ratio 5:1; D = d = 0.3 centimeter; L = 10 centimeters.
Series of pictures (c) show resonator end closed. For various distances between nozzle and tube (l/d), note structure of gas jets and different degrees of heating of surrounding air at wall of tube into which heat is pumped in oscillation process (see fig. 3). Series of pictures (b) are with resonator partially open, with throttle of 0.15-centimeter diameter; adjusted for l = 4 d = 1.2 centimeter. Various phases of periodic processes can be seen. Approximately 30 percent of the expanding gas mass escapes from throttle as pulsating jet at 12° C heating, with occasional above-critical pressure ratio. 70 Percent of gas flows off in region of pipe mouth, cooling (after mixing of partial streams II and II) approximately 5° C; compare figure 3 and separation characteristic on figure 14. During oscillation process intense ultrasonic impulses (frequency about 30 kcps) also arise; spherical waves and reflection at supporting disk are seen in meridional section.

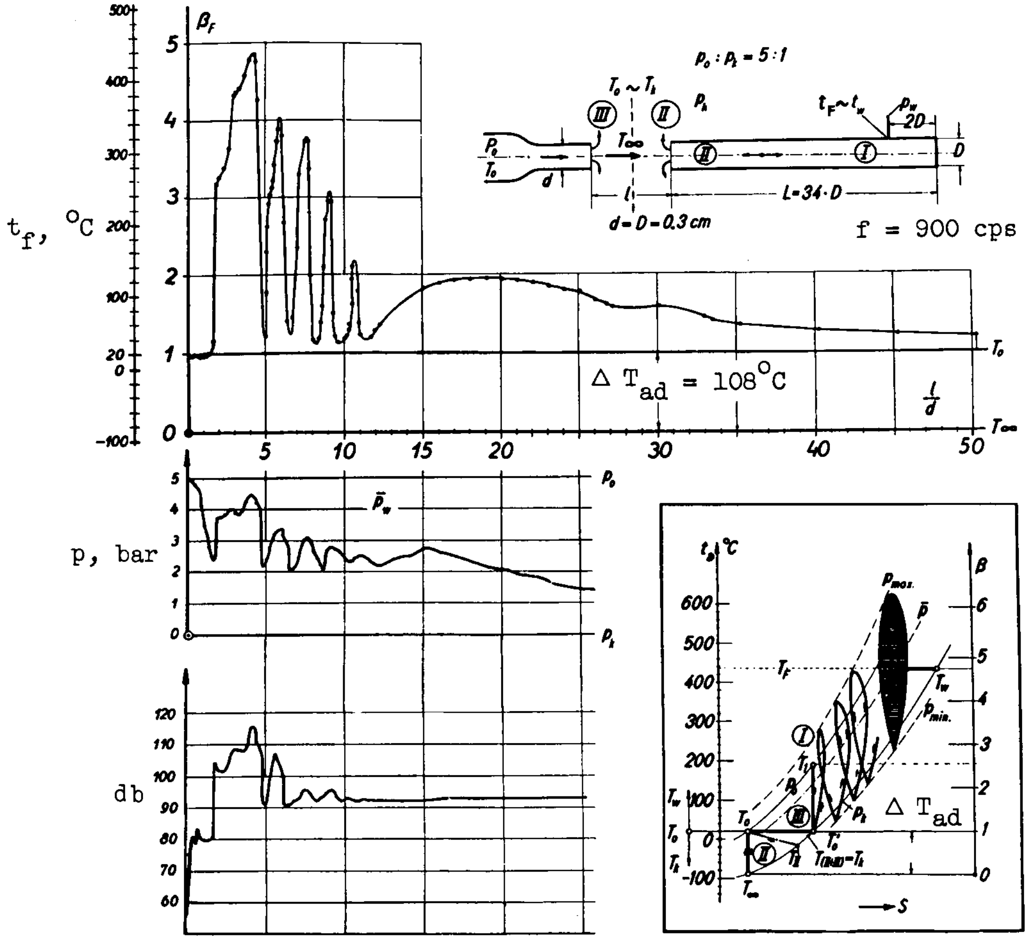


Figure 3. - Measurements on 900-cps resonance tube. $p_0/p_k = 5$; d = D = 0.3 centimeter; L = 10.2 centimeter.
Tube wall temperature and "mean" gas pressure in region of closed end of tube and total sound intensity measured at side of nozzle at 100 centimeter distance are plotted. Values are represented as a function of distance ratio l/d. (On lower right are shown processes in resonance tubes, according to idea of author, as a strongly schematized entropy diagram.)

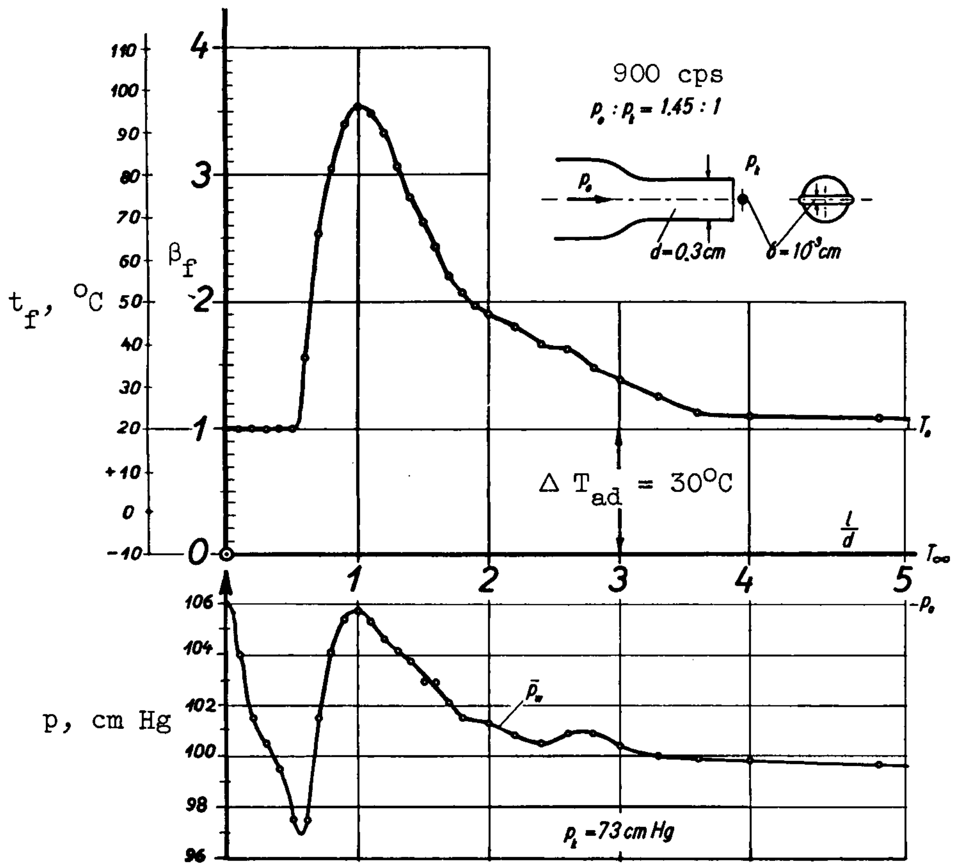


Figure 4. - 900-cps Resonance tube. Measurements analogous to those of figure 3 but for a below-critical nozzle pressure ratio; oscillation excited by a thin nylon thread stretched across the nozzle exit area. f, 900 cps.

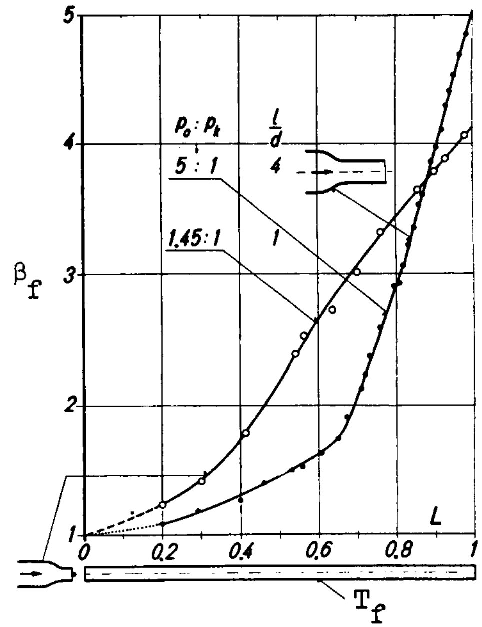


Figure 5. - Temperature distribution on resonator surface plotted over tube length, L. Temperatures are measured under same operating conditions as for figures 3 and 4, namely, in settings with optimal heating. f, 900 cps.

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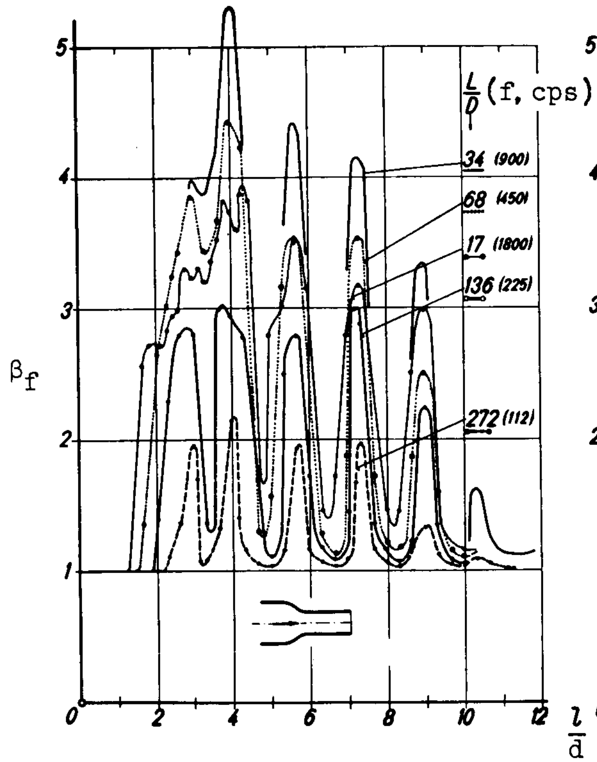

Figure 6. - Wall temperatures at closed end of tube resonators of various lengths. L/D, percent tube length; corresponding fundamental frequences are given in parentheses (f in cps). p_0/p_k, 5:1; $\Delta\ T_{ad}$, 108° C.

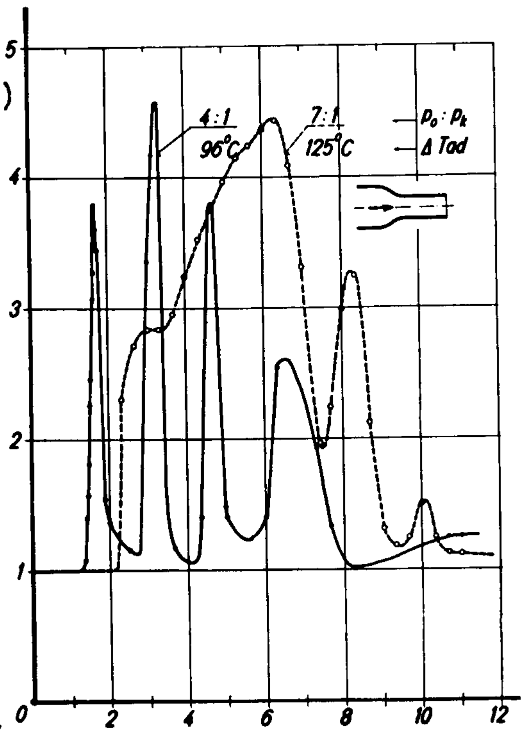

Figure 7. - Wall temperatures at closed end of resonator for above-critical nozzle jets for different pressure ratios. f, 900 cps.

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CZ-3 back

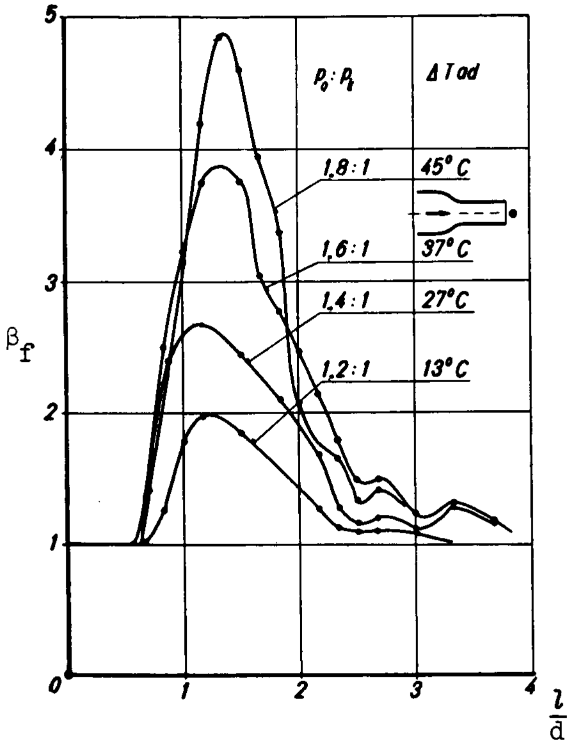

Figure 8. - Wall temperatures at closed end of resonator for four below-critical nozzle pressure ratios. Oscillations excited with turbulence thread. f, 900 cps.

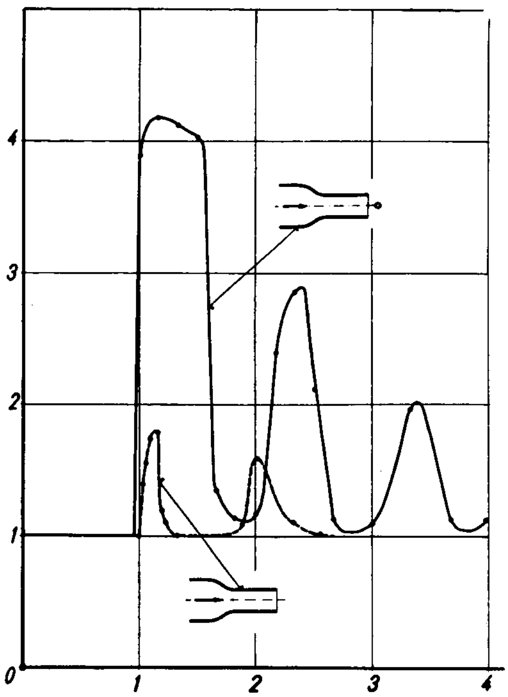

Figure 9. - Wall temperature at closed end of resonator for nozzle pressure ratio 3:1 without and with excitation of oscillations by turbulence thread. p_0/p_k, 3:1; ΔT_{ad}, 79° C; f, 900 cps.

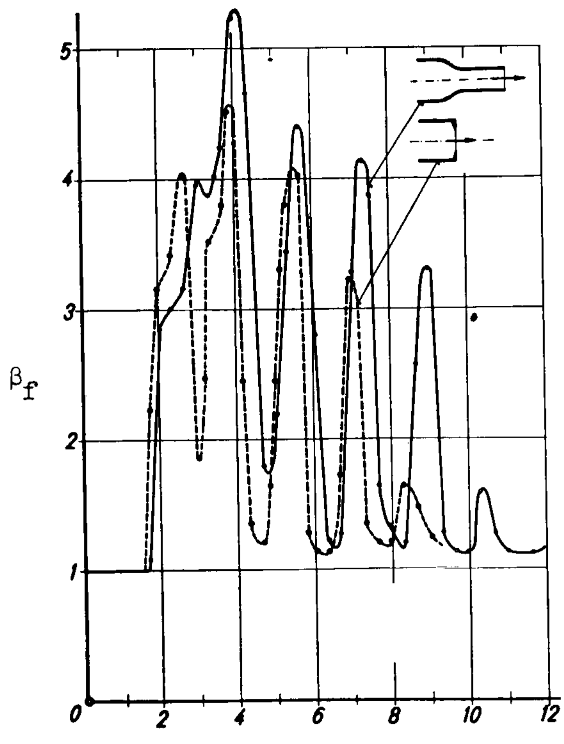

Figure 10. - Wall temperature at closed end of resonator for air jets that were produced with a nozzle and in a sharp-edged diaphragm, p_0/p_k, 5:1; ΔT_{ad}, 108° C; f, 900 cps.

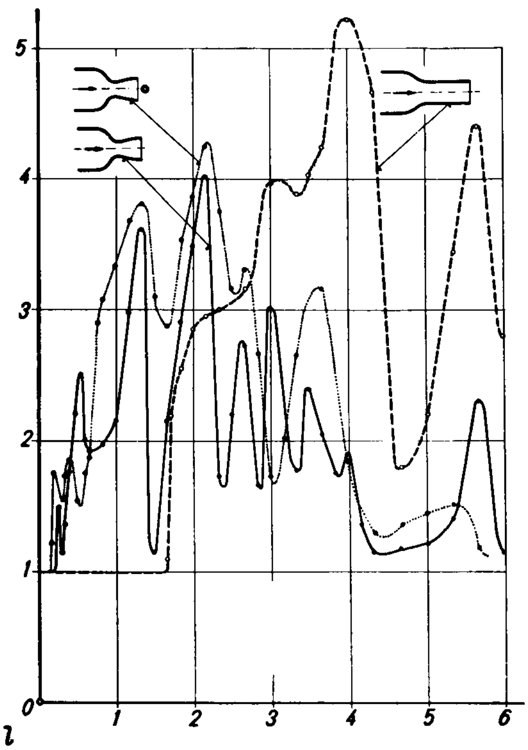

Figure 11. - Wall temperature at closed end of resonance tube for air jet with homogeneous supersonic velocity; Laval nozzle for 1.7 times sound velocity without and with excitation of oscillations by turbulence thread. Curve for nozzle with parallel duct (for equal pressure ratio 5:1) serves for comparison. p_0/p_k, 5:1; ΔT_{ad}, 108° C; f, 900 cps.

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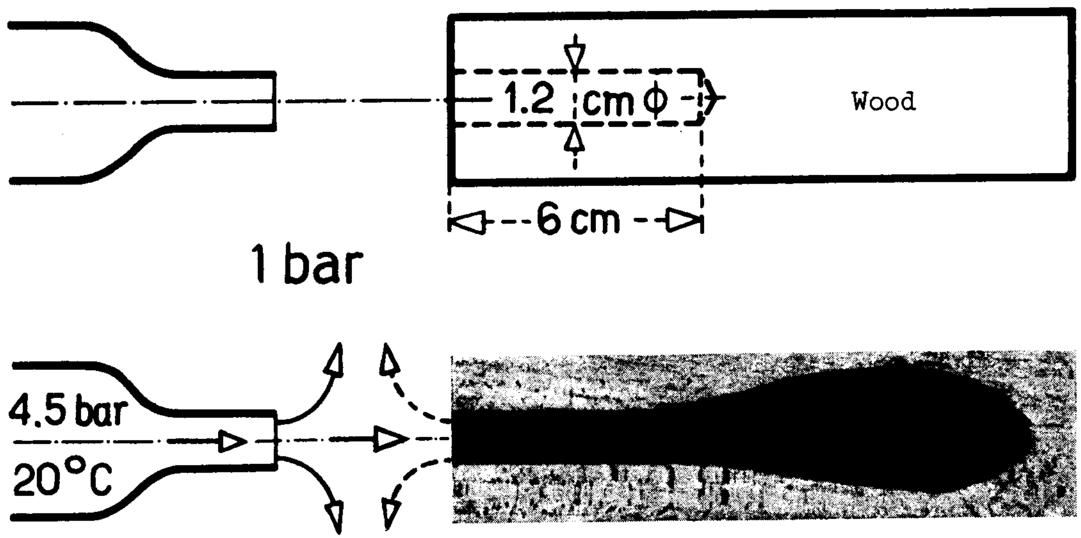

Figure 12. - Burned-out cavity produced in 30 seconds by resonance-tube process in a piece of wood. (Piece was sawed along axis of drilled hole.)

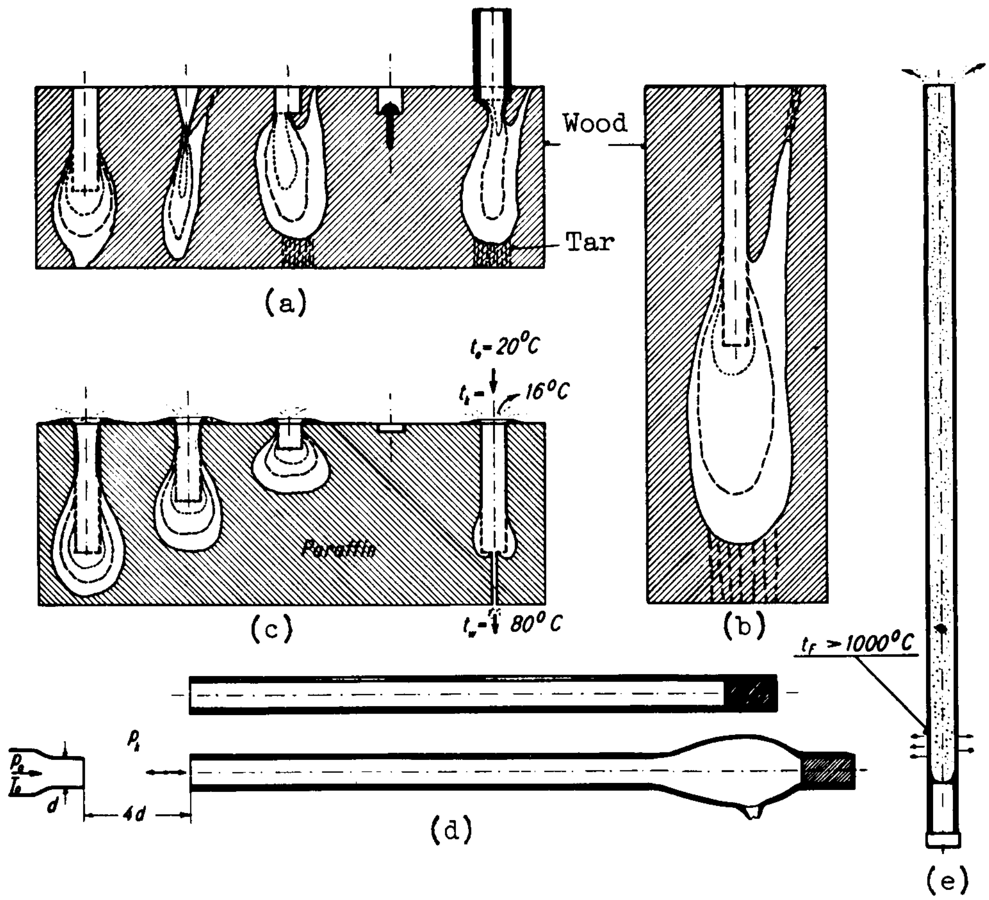

Figure 13. - Thermal effects in resonance tubes. (a) and (b) Burned-out cavities in wood and means for weakening the process. (c) Melting processes in paraffin; holes are enlarged; separation into a warm and cool stream for only partially closed end of the resonator. (d) Deformations of thermoplastic tube. (e) Nickel silver tube glows and melts if dust particles (e.g., soldering tin) vibrate along resonance cavity. p_0/p_k, 5:1 l/d, 4; d = D = 0.3 centimeter.

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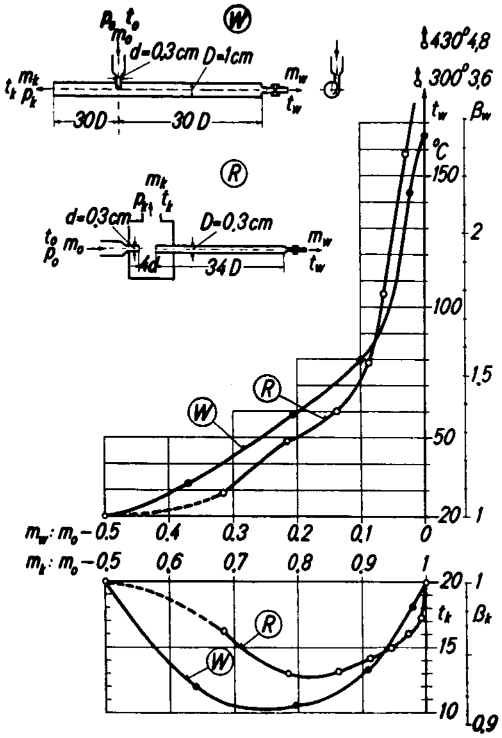

Figure 14. - Separation of expanding air jet into heated and cooled partial gas mass; operating characteristics of vortex tube and of 900-cps resonator tube, both of simplest construction. (On cold side, temperature scales are magnified five times.) p_0/p_k, 5:1; ΔT_{ad}, 108° C.